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学位論文要旨

ABSTRACT

Recently, the use of electric devices is increasing in the electronics, information, and communications areas. These electric devices emit electromagnetic waves and there are waves leaking from some electric devices.

To simulate an electromagnetic field in a material, we have to use electric parameters of the material. But there are many materials available with compounded materials and there are many types of materials, such as metals, cloths, and liquids.

We have suggested estimation methods and developed an estimation system of the electric parameters for many types of materials such as metallic materials, thin cloths, and liquid materials. For estimation, we measured the Shielding Effectiveness (*SE*) using a shield box, and calculated the *SE* fitted to the measured *SE*. The *SE* of the materials was measured as a function of frequency, and the results were compared with the calculated solutions for a multi-layered model that was evaluated using the Sommerfeld integral that expresses near-field spherical waves by a composition of cylindrical waves. For numerical analysis, we modeled the materials and shield box as thin homogeneous layers. Then, we calculated the electromagnetic fields using the Sommerfeld integral.

To evaluate our estimation method, we compare the estimated values with the nominal values. For the non-magnetic materials, the estimated relative permeability was the same as the nominal values. For the ferromagnetic materials, the estimated relative permeability varied 0% to 30% from the nominal values. For both types of materials, the estimated conductivities were 0% to 9.8% different from nominal values. Next, we apply our estimation method to shielding sheets, and we can estimate the electric parameters for items such as thin cloths. Then, we estimate the dielectric constant for liquid materials. The accuracy is such that the estimated value is different from the nominal value by less than 2%. These results show that we have successfully developed an estimation system of electric parameters for these cases.

1. Introduction

With the continuing development of information and electrical technology, the number and kinds of electric devices in our society have increased rapidly. It has been shown that electromagnetic waves leaking from electronic devices may cause incorrect operation of other electronic devices. One method to eliminate the electromagnetic noise which is emitted from electric devices is the use of an electromagnetic shielding sheet. In order to eliminate the electromagnetic noise, the design of the electromagnetic shielding sheet must take into account the electromagnetic field from various noise source points. To do this properly, we must investigate the propagation mechanism of the electromagnetic wave by using numerical analysis. Then it is important to know the electric parameters (ε_r, μ_r, σ), because they are used for calculation of the electromagnetic field.

The classical investigation of the effect of a finite conducting plane upon the radiation of an oscillating dipole was published by Arnold Sommerfeld in 1909 [1]. Since that time an enormous amount of work has appeared on the subject and it may be fairly said that no aspect of the problem of radio wave propagation has received more careful attention. For calculating the electromagnetic field, we consider the location of the observation point, because calculations of the near-field point and a distant point are quite different. Therefore, we consider that point and we calculate the Sommerfeld integration model that can expresses a spherical wave by compositions of cylindrical waves.

In this research, we used a shield box in order to easily measure the Shielding Effectiveness (*SE*). We estimated the electric parameters by considering the propagation of waves through metallic materials [2], thin shielding sheets [3], and liquid materials [4] [5]. For the numerical calculations, we had to consider the location of the source, and we used the Sommerfeld integral that expresses spherical waves by compositions of cylindrical waves [6]. We fitted the calculated values to measurement values, and we were able to estimate the electric parameters. We then evaluated our method by comparing the values obtained by our method with the nominal values [7]. Finally, we concluded that we had developed a successful estimation system [8].

2. Estimation of Relative Permeability and Conductivity of Thin Materials

In this chapter, we suggest the estimation method of relative permeability and conductivity for metallic materials and thin shielding sheets, and develop an estimation system.

For estimation, we measured the *SE* using a shield box, and calculated the *SE* fitted to the measured *SE*. The best fitted values are the estimated values. For measurement of *SE* for magnetic fields, we used the shield box which we have developed. A transmitter and a receiver are located in the shield box. The planes of the transmitting and receiving loop antennas and the testing materials are parallel in the shield box. The *SE* of the magnetic field is expressed by eq. (1). The *SE* is defined as the ratio of the magnetic field strength at the receiver without the testing material (H_0) to that with the testing material (H_1).

$$SE = 20\log_{10}\frac{|H_0|}{|H_1|} \qquad \text{[dB]} \tag{1}$$

In calculating an electromagnetic field, we have to consider the locations of the source and the observation point, because the calculations of an electromagnetic field for a near-field point and that for a distant point are quite different. If the distance z from the observation point to a source with wave length λ is $z \gg \lambda/2\pi$, the radiated field is the dominant wave

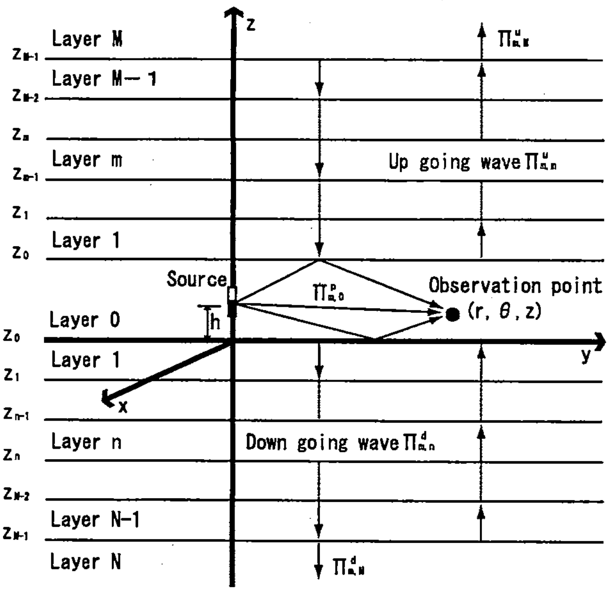

Figure 1: Multi-layered model

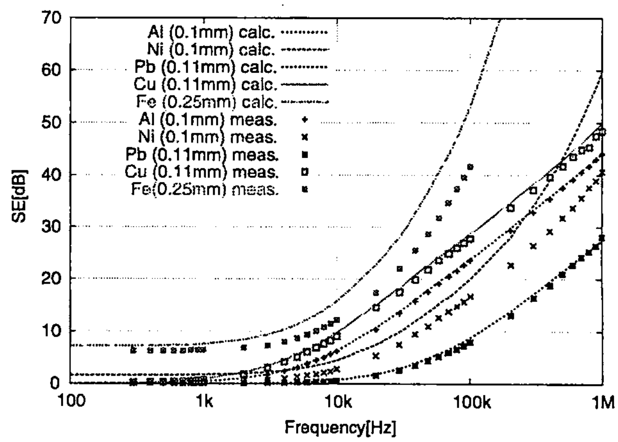

Figure 2: *SE* of metallic materials

emitted from the source and can be regarded as a plane wave. In this case, the *SE* of the shielding material is not related to the position of the source. But in the shield boxes we used, the distance of the source from the observation point is $z \ll \lambda/2\pi$, and it can not be considered that the radiated field is the wave emitted from source. Thus it is necessary to calculate the electromagnetic field of a near source when calculating *SE*. In this research in consideration of the near source, we used the Sommerfeld integral that expresses spherical waves by a composition of cylindrical waves.

Our calculation model is the Multi-layered model shown in fig. 1. The source is assumed to be at $z=h$ with homogeneous layers above and below the dipole extending to infinity in the horizontal directions. The axial direction of the dipole source is located vertically perpendicular to each layer. Π_i expresses the Hertz vector in the ith layer. The superscript u identifies the up-going wave; d is the down-going wave, and p is the direct wave.

SE has different characteristics as a function of frequency for different types of materials. Fig. 2 shows *SE* of metallic materials. In the case of non-magnetic materials (Al, Pb, Cu), the measurement value and the calculation value that used the nominal value of the electric parameters are very close. In these cases, we can estimate the electric parameters with high accuracy. But for ferromagnetic materials, as the frequency becomes high, the calculated *SE* becomes much larger than the measured *SE*. The reasons for the difference have no relation to the circumference of the box [9].

Therefore, we then calculated *SE* by taking the frequency characteristics into account [2]. Fig. 3 shows *SE* when the frequency characteristics of the relative permeability were considered. From fig. 2 in the low frequency region where the calculated and measured *SE* values were close, we used the estimation method to determine the conductivity which does not change with frequency. Using the conductivity as a constant, we then varied the relative permeability to find the minimum value of the difference. In this computation, we used the least squares method. In this way, by changing the relative permeability parameter, we can estimate the frequency characteristics of the relative permeability as shown in Fig. 4. Since most of the data of relative permeability available in reference books are for DC, we

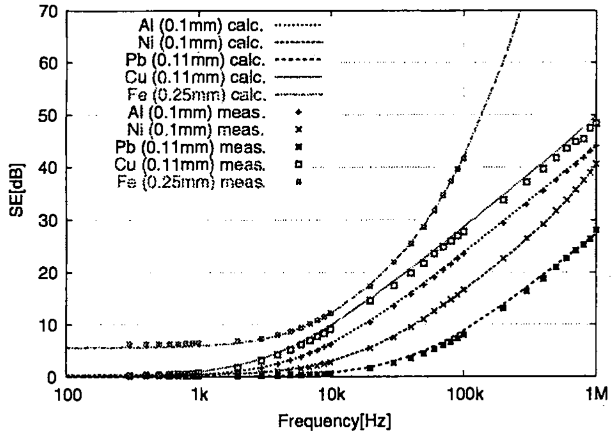

Figure 3: *SE* of metallic materials after consideration of frequency characteristics

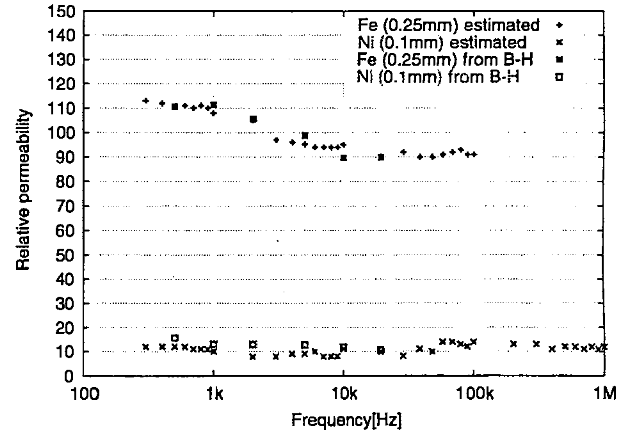

Figure 4: The frequency characteristics of the relative permeability

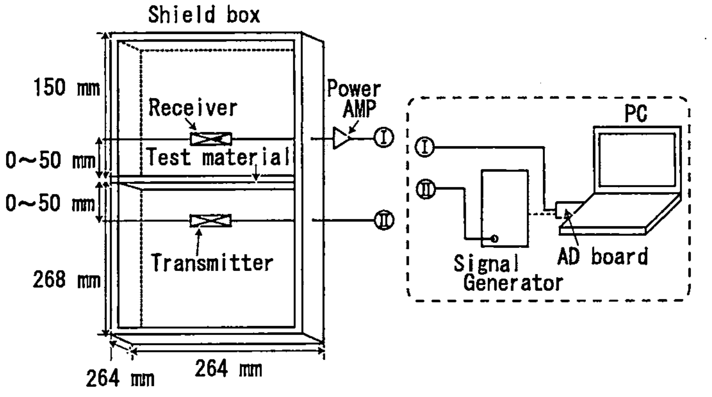

Figure 5: Estimation system of relative permeability and conductivity

have to determine for ourselves the nominal values for the AC case. In order to determine the nominal values for the AC case, we determined the relative permeability as a function of frequency by using *B–H* curve generators. When this was completed, we evaluated our estimation method.

Table 1 shows the relative permeability and conductivity of metallic materials. The calculated conductivity was the same as the nominal value for Pb, 1.9% greater for Cu, and 3.3% greater for Al. For the ferromagnetic materials, the calculated value was 4.1% higher for Ni and 9.8% higher for Fe. For comparison, measurement of conductivity using the four point probe method had a typical error rate of about 20%. Thus, we find that our method is better than the existing method. The nominal values for the relative permeability of the ferromagnetic materials are close to the values derived with our *B–H* curve testing as shown in Fig. 4. For Fe, the nominal and calculated values ranged from the same to 3% difference. For Ni, they ranged from the same to 33% difference from the nominal values. Then, next we apply it to the shielding sheets and estimate the electric parameters. Table 2 shows the results of estimation of electric parameters for thin shielding sheets.

Our estimation system consists of two parts as shown in fig. 5. One is the measurement system of *SE*; and the other is the calculation of the electric parameters. The *SE* is measured by using the shield box. The PC both gathers the data for the measured *SE* and estimates the electric parameters. For the case of non-magnetic materials, it takes one and a half minutes using our system to estimate the relative permeability and the conductivity for materials. For the case of magnetic materials, it takes two minutes using our system to estimate the relative permeability with frequency characteristics and the conductivity. The results are not different from the results using the spectrum analyzer system. As PC technology has advanced, we can now do the calculations on a PC and we do not need to use an expensive machine such as a workstation. And we can easily do a complex calculation such as a multi-layered problem using a Sommerfeld integral.

Table 1: Nominal electric parameter values compared to estimated values

Materials (thickness)	μ_r [nom. / cal.]	σ [S / m] [nom. / cal.]
Al (0.1 mm)	1.0 / 1.0	3.63×10^7 / 3.51×10^7
Cu (0.11 mm)	1.0 / 1.0	5.80×10^7 / 5.69×10^7
Pb (0.11 mm)	1.0 / 1.0	0.50×10^7 / 0.50×10^7
Fe (0.25 mm)	111.0 / 108.0	1.02×10^7 / 0.92×10^7
Ni (0.1 mm)	13.0 / 10.0	1.45×10^7 / 1.39×10^7

Table 2: Results of estimation for thin shielding sheets

Material (thickness)	μ_r	σ [S / m]
Su-80-301 (0.085mm)	1.0	4.38×10^5
Su-4x-8055 (0.08mm)	1.0	2.17×10^5
Si-80-301 (0.085mm)	1.0	3.10×10^5
Sui-10-56 (0.125mm)	1.0	8.80×10^4
Sui13-30FR (0.135mm)	2.0	2.55×10^5

3. Estimation of Relative Dielectric Constant of Liquid Materials

In this chapter, we suggest the estimation method of relative dielectric constant for liquid materials, and develop an estimation system.

For estimation, we use a procedure similar to that used in chapter 3. The *SE* of the electric field is expressed by eq. (2). The *SE* is similarly defined as the ratio of the electric field strength at the receiver without the testing material (E_0) to that with the testing material (E_1). For the measurement *SE* of liquid materials, we used a container made of acrylic that has no influence on *SE*.

$$SE = 20\log_{10}\frac{|E_0|}{|E_1|} \qquad \text{[dB]} \tag{2}$$

Our calculation model is the multi-layered model using an electric dipole source. The *SE* has different characteristics as a function of frequency for different types of materials. Fig. 6 shows the *SE* of liquid materials. The measurement value and the calculation value are very close.

Table 3 shows the dielectric constant of liquid materials. The estimated dielectric constant was the same as the nominal value for Glycerin, 1.2% smaller for pure water, and 2.0% greater

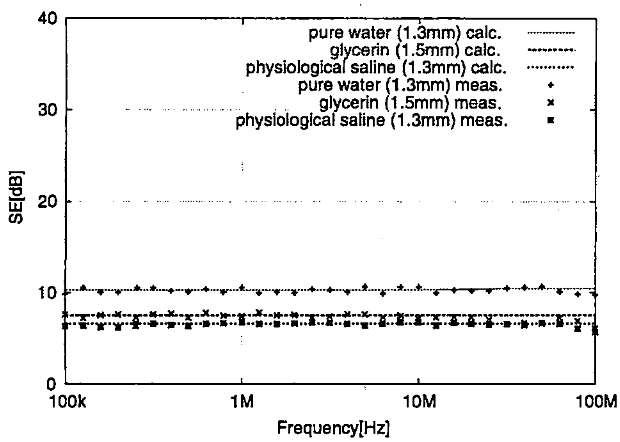

Figure 6: *SE* of liquid materials

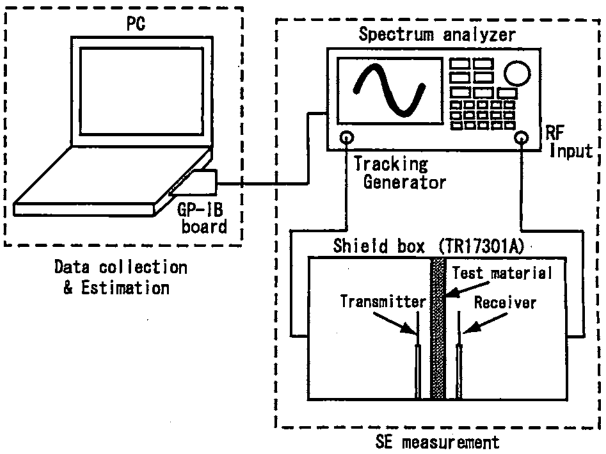

Figure 7: Estimation system of relative dielectric constan

Table 3: Nominal relative dielectric constant compared with estimated values

material (thickness)	ε_r [nom. / est.]
Pure water (1.3 mm)	81.0 / 80.0
Glycerin (1.5 mm)	50.0 / 50.0
Physiological saline (1.3 mm)	49.0 / 50.0

for physiological saline (1.2wt% NaCl). The values of the conductivity of the liquid materials are very small. Most of the conductivities of liquid materials are less than 2 $[S/m]$.

Next we developed the estimation system [10]. Our estimation system consists of two parts as shown in fig. 7. One is the measurement system of *SE*; and the other is the calculation of the electric parameters. The *SE* is measured by using the shield box. The PC both gathers the data for the measured *SE* and estimates the electric parameters. For estimation, it takes between one and two minutes using our system to estimate the relative dielectric constant for liquid materials. The results are not different from the results using the spectrum analyzer system. As PC technology has advanced, we can now do the calculations on a PC and we do not need to use an expensive machine such as a workstation.

4. Conclusion

We measured *SE* using a shield box. Since near-field and far-field calculation methods are different, we had to consider the distance from the source to the observation point. For our measurements, the distances from the dipole source to the observation point are smaller than a wave length. We calculated the electromagnetic field at the observation point by using the Sommerfeld integral that expresses spherical waves as compositions of cylindrical waves.

Measurement values of the non-magnetic materials and the liquid materials of *SE* are very close to the calculated *SE* values using nominal electric parameters, and we were able to estimate the electric parameters easily. But in the case of ferromagnetic materials, the measurement values and the calculated values differ as the frequency increases. When we considered the frequency characteristics of the electric parameters, changing the parameters allowed us to determine the relative permeability and conductivity as a function of frequency.

Finally, we developed the estimation system for both two types.

Using our method, we can estimate the electric parameters not only for non-magnetic materials and liquid materials but also for ferromagnetic materials. This will be very useful for the simulation of electromagnetic fields. And we hope that the present experimental studies help simulate an electromagnetic field's effect on a human's body and improve measures for EMC.

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学位論文審査結果の要旨

平成 17 年 1 月 25 日に第 1 回学位論文審査委員会を開催、平成 17 年 1 月 26 日に口頭発表、その後に第 2 回審査委員会を開催し、慎重審議の結果以下の通り判定した。なお、口頭発表における質疑を最終試験に代えるものとした。

不要電磁界ノイズを防ぐためには電磁シールド材が用いられるが、そのシールド効果を評価するためには、シールド材の電気定数を知ることが必要になる。本論文は、シールド材の電気定数の推定法、及び推定システムの構築法に関してまとめたものである。本推定法では電磁シールド材のシールド効果を実測し、その値と電磁界理論解析による計算値を一致させることによって、シールド材の電気定数を逆問題として推定した。その結果、金属シールド材の導電率及び透磁率を、周波数特性を含めて推定することに成功した。また、非接触で液体の非誘電率を推定することにも成功した。一方で、従来大掛かりな装置が必要であった「シールド効果の測定」を含め、「複雑な電磁界計算」及び「電気定数の推定」の一連の作業を全てパソコン上で実行できるポータブルな「電気定数推定システム」を世界で初めて構築した。

この研究成果は、従来から電磁シールド材として用いられている金属板だけでなく、シールド効果を持つ布や液体の電気定数も推定できるという技術開発に貢献しただけではなく、本手法を用いることにより、これまで困難であった任意形状を持つシールド材の電磁界シミュレーションを容易に行うことができるようになる。

以上の内容から、本論文は博士（工学）に値するものと判定した。